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RESEARCH ON OPTIMAL CONTROL, STABILIZATION, AND COMPUTATIONAL ALGORITHMS FOR AEROSPACE APPLICATIONS

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ABSTRACT

This document is the final report on NASA grant NGL-22-009-124 to the Laboratory for Information and Decision Systems, LIDS, (formerly the Electronic Systems Laboratory) of the Massachusetts Institute of Technology.

This grant was initiated in 1966 under the initial auspices of the now defunct NASA Electronic Systems Center, and continued later on under the auspices of the NASA Ames Research Center. During the last three years of the grant, support was also provided by the NASA Langley Research Center. The grant terminated on 31 May 1984. During it's 18 year tenure a total of $1,306.732 were spent, including some MIT cost-sharing.

In this final report we overview the research carried out in the areas of optimal control and estimation theory and its applications under this grant. We also provide a listing of the 257 publications that document the research results. Finally, we present the list of the 80 MIT faculty, post-doctoral staff, and graduate students that participated in this research.

FOREWORD

This document is the final report on NASA grant NGL-22-009-124 to the Laboratory for Information and Decision Systems, LIDS, (formerly the Electronic Systems Laboratory) of the Massachusetts Institute of Technology.

This grant was initiated in 1966 under the initial auspices of the now defunct NASA Electronic Systems Center, and continued later on under the auspices of the NASA Ames Research Center. During the last three years of the grant, support was also provided by the NASA Langley Research Center. The grant terminated on 31 May 1984. During it's 18 year tenure a total of $1,306.732 were spent, including some MIT cost-sharing.

NASA regulations, in their infinite wisdom, offer significant flexibility to the Principal Investigator on the style of the final report. With the encouragement and support of my grant monitors I have decided to adopt a historical, and sometimes philosophical, perspective on the research carried out at MIT/LIDS during the 18 year life of this grant.

The story of this grant is both remarkable and wonderful. Its contributions to Modern Control Theory and Engineering strongly parallel those of the international developments in this still very exciting field. This became possible because of the close interactions between the several NASA grant monitors and the members of the MIT/LIDS control group. We were allowed wide latitude in pursuing promising theoretical directions and feasibility studies. On the other hand, there was a very conscious effort to be aware in detail of the changing control system design environment and types of applications faced by the NASA centers in general, and our sponsors divisions in particular. This two-way exchange lasted for 18 years and has resulted in solid achievements. Perhaps this grant can be a model for successful research cooperation between research sponsors and universities.

Of course, the primary objective of federally funded research is to carry basic research so as to advance the state of knowledge in selected areas: in our case, control theory and its applications. The 257 reports, theses, conference papers, and journal articles, listed in the Publications section, document the broad technical achievements of our research. It is a fact that this NASA grant has been the primary reason for the leadership position that the MIT/LIDS control group enjoys among the several international centers of excellence in control theory. The rolling three-year step-funded nature of this grant guaranteed some longevity so that risky ideas could be examined and developed. In addition, by carrying out feasibility studies for different applications of direct interest to NASA, and by bouncing-off our findings to our NASA colleagues, we always had a pretty good idea of the strengths and weaknesses for our theory when applied to realistic settings. This helped us to channel our energies to basic research directions that would have an obvious relevance in the long run, and to avoid pursuing mathematically elegant theories whose assumptions violated common engineering considerations.

There is a different, but in the long run probably more important, dimension in research funding at universities, namely the support of graduate students. This grant has supported the research of dozens of M.S. and Ph.D. students. Perhaps the most remarkable by-product of this grant is the full or partial support that it provided to 51 MIT Ph.D. students (see People section), most of whom already have distinguished careers in academia and industry. The research and development accomplishments of these alumni, after they left MIT, is a remarkable achievement in itself.

Finally, although NASA grant NGL-22-009-124 terminated on 31 May 1984 (so as not to drive the auditors crazy), a new NASA grant NAG 2-297, became effective on 1 June 1984. The author sincerely hopes that several years from now a similar story can be told.

ACKNOWLEDGMENTS

Several colleagues, both at NASA and at MIT, have contributed to the research carried out with support from this grant, and they deserve special recognition.

At the NASA Electronics Research Center I wish to thank George Kovatch (grant monitor), Hugo Schuck, George Zames, and Bill Wolovich.

At the NASA Ames Research Center I wish to thank Brian Doolin (grant monitor), Luigi Cicolani (grant monitor), George Meyer (grant monitor), Heinz Erzberger, Al Smith, and Jack Franklin.

At the NASA Langley Research Center I wish to thank Jerry Elliott (grant monitor), Ray Montgomery, Larry Taylor, Al Schy and Ernie Armstrong.

At MIT special thanks are due to Roger Brockett, Sanjoy Mitter, and Alan Willsky who acted, at different times, as co-principal investigators with me and actively contributed to the overall research effort. In addition, the following MIT colleagues devoted a significant amount of their research time to the diverse topics pursued under this grant: Jan Willems, Ian Rhodes, Tim Johnson, Nils Sandell, Alan Laub, Michael Triantafyllou, and Lena Valavani. Special thanks are due to Gunter Stein for injecting fresh insight to control theory and practice.

Finally, the author wants to thank the several dozen MIT graduate students that generated the majority of our research findings in the course of their thesis research.

1. RESEARCH OVERVIEW

1.1 Introduction

In this section we attempt to provide a brief summary of the diverse research topics that received attention during the lifetime of this grant. Clearly, we can only scratch the surface. Even to summarize each one of the 257 publications would represent an immense effort. For these reasons, the author has decided to divide the research carned out into twelve subareas, and to assign each publication to one of the twelve research areas. This is somewhat misleading, because the vast majority of the publications cannot fit neatly into a well-defined theoretical or practical pigeon-hole.

Within each specific research topic we shall list the relevant publications. We shall not discuss the specific contributions contained in each publication. Rather, we shall overview their collective impact upon the field. Whenever appropriate we shall "flag" a particular publication as representing, in the author's opinion, a significant turning point in our research directions. Since the alumni of this grant (see People section) represent a very select subset of respected researchers, the author sincerely hopes that the absence of a "flag" for a particular publication does not mean that the results contained therein were not noteworthy, novel, exciting, or advancing the state-of-the-art.

The twelve research topics are as follows:

1. Stability Theory
2. Optimal Estimation and Control Theory
3. Distributed Parameter Systems Theory
4. Adaptive Control Systems

5. Large Scale Systems
6. Failure-Detection and Fault-Tolerant Control
7. Multivariable Linear Feedback Control Systems
8. Air Traffic Control Studies
9. Space Systems Studies
10. Aircraft Systems Control Studies
11. Digital Implementation Issues
12. Numerical Methods for Estimation and Control.

The reader will notice that topics (1)-(3) contain the word "theory", while topics (4)-(7) do not. This does not mean that the publications in topics (4)-(7) are not theoretical in nature; on the contrary most of them are. However, in the classification scheme selected (for better or for worse) by the author the theoretical results of topics (1)-(3) were focused in particular classes of problems. Indeed several publications in topics (4)-(7) illustrate the theory contained therein by numerical simulations using both academic and quasi-realistic examples. Also, the reader will note a change in the presentation style. Theory is theory. Theory applied to a class of problems is something else.

Topics (8)-(10) contain the word "studies". The pertinent publications listed in topics (8)-(10) were even more focused into the types of specific systems that were of interest to the particular interests of the NASA grant monitors, and their NASA colleagues, at a particular time period. The author has chosen the word "studies" rather than "applications" although many of the publications use realistic numerical models of specific physical systems. It is more appropriate to view these publications as "feasibility studies," rather than "applications." This reflects the strong

bias of the author that universities (at least the LIDS group at MIT) cannot and should not do real applications; industry does applications. Fortunately, all the NASA grant monitors over this 18 year period shared the philosophy of the author.

These "studies" greatly influenced the selection of theoretical research topics by examining the strengths and limitations of new theories in a more pragmatic setting. Some of these "studies" did have a direct influence upon the work of our NASA colleagues, and upon subsequent industrial applications.

Finally, topics (11) and (12) reflect the importance of reliable number-crunching at both the computer-aided analysis and design phase, and the real-time microprocessor-based digital control system design.

1.2 Background

In order to place the research at a proper prespective, it is important to present a brief overview of the status of the field in the few years before the grant initiation date (1966).

Servomechanism control system design, for Single-Input-Single-Output (SISO) for Linear Time Invariant (LTI) feedback control systems had reached a certain degree of maturity by the late fifties. Several dozen books were written on the subject, and it was routinely taught as an undergraduate elective in several engineering departments. Practical control systems were designed using Root Locus techniques, Bode diagrams, and Nichols charts. Designs were tested using analog computers. For nonlinear SISO control systems the describing function method was used to predict the onset of possible oscillations. Some phase plane methods were used to study nonlinear second-order systems, and relay servomechanisms.

During the time period 1958-1966 the action was in modern control and estimation theory. The celebrated maximum principle of Pontryagin et al and the dynamic programming methodology of Bellman provided a solid theoretical foundation for the study of nonlinear Multi-Input-Multi-Output (MIMO) control systems.

For linear SISO and MIMO systems, the pioneering work of Kalman et al on state variable representations, structural properties, (controllability, observability), state-variable feedback via the Linear-Quadratic regulator (LQR) and linear optimal state estimation (the Kalman filter) provided a wealth of new results and approaches that would keep theoreticians and practitioners busy for many years to come. The underlying theory for minimum-time, minimum-fuel, and minimum-energy problems was worked out. In 1961 the so-called Linear-Quadratic-Gaussian (LQG) approach to MIMO control system design was developed, independently and simultaneously, by Gunkell and Franklin and by Joseph and Tou (it took another decade to prove all the results rigourously).

The stability theory of nonlinear systems was also booming. Lyapunov methods became very popular. The input-output approach to stability (Zames, Sandberg), was published in 1966. Frequency-domain criteria (Popov criterion, circle criteria) were just developed.

The development of computer-aided design software on maxi-computers for calculating the numerical solutions to optimal estimation and control problems was at its infancy; after all FORTRAN was only a few years old.

A few "preliminary feasibility" studies, primarily related to navigation and optimal guidance trajectories, were carried out with mixed results; they pointed

out that the new powerful theoretical results had to be used with care in practical settings and pointed out the need for ad-hoc adjustments to the theoretical results (i.e. how to pick the process noise covariance matrix so that Kalman filters would not diverge).

Several notable research monographs appeared in the early sixties; Bellman (1957), Chang (1961), Pontryagin et al (1962), Leitman (1962), Tou (1962), Balakrishnan and Neustadt (1963). Textbooks were lagging somewhat; Zadeh and Desoer (1964), Athans and Falb (1966), Lee and Marcus (1967), Bryson and Ho (1969). Regular graduate level subjects on modern control theory began to be taught in the major research universities from 1965 on.

The research in the early sixties provided a much needed stimulus to control theory. Coupled with the increasing emphasis upon space systems and other defense applications, as well as the rapid changes in digital computer technology, there was a lot of excitement and promise in the air.

NASA established within the Electronics Research Center, in Cambridge, Mass., the Office of Control Theory and Applications (OCTA). The present grant to MIT was originally funded through NASA/ERC and the first grant monitors were Dr. George Kovatch, Dr. George Zames, and Dr. William A. Wolovich. At the grant inception, Prof. Roger W. Brockett was principal co-investigator.

1.3 Stability Theory

The following publications fall (more or less) in this topic; [7],[8],[9],[13], [14],[21],[29],[30],[36],[38],[45],[54],[63],[73],[78],[92],[118],[157],[169],[189], [208].

During the late sixties the theoretical research on nonlinear system theory was spearheaded by Professor Roger W. Brockett and his students. The effort was significantly strengthened when Jan C. Willems joined the MIT faculty after receiving his Ph.D. under the supervision of Professor Brockett. The main research emphasis during these early years was upon improving upon the earlier results related to the stability of nonlinear systems using both time-domain and frequency-domain ideas.

Notable contributions are: the paper by Brockett and Lee [9] that developed frequency domain criteria for the instability of nonlinear and time varying dynamic systems; the paper by Willems and Brockett [36] on stability theory; and the "classic" paper by Willems [54] on the relations between causality, stability, and invertibility.

With the departure of both Professors Brockett and Willems from MIT the research on stability theory was reduced. The emphasis shifted more to questions related to stochastic stability as can by evidenced by the Ph.D. theses of Blankenship [78] and Martin [118].

Our brief overview of the stability research concludes with the conic sector stability results obtained by Safonov in his Ph.D. thesis [169], also documented in his research monograph [201], and [208]. These results generalize the 1966 results of Zames. Interestingly, the conic sector stability results were obtained by Safonov in his attempt to streamline the proofs associated with the guaranteed robustness properties of LQG regulators (see also Section 1.9).

1.4 Optimal Estimation and Control Theory

In this section we overview the basic research on optimal control and estimation theory. We should remark that in this section we do not include results that pertain

to LQG-type of problems; these will be overviewed in Section 1.9. Similarly, results that pertain to optimization issues for distributed parameter systems, large scale systems, and reliable systems will be overviewed separately.

Even with this division, the number of publications is very large, and the following publications fall in this research category: [2],[10],[11],[12],[17],[18], [19],[20],[23],[24],[25],[32],[33],[35],[37],[40],[46],[48],[56],[57],[61],[62],[65], [71],[72],[74],[75],[77],[82],[85],[87],[96],[99],[100],[106],[107],[108],[115],[117], [120],[121],[127],[128],[129],[130],[134],[141],[142],[145],[151],[164],[165],[166], [171],[174],[177],[181],[182],[183],[192],[197],[202],[205],[211],[218],[225],[229], [236],[238], and [253].

The research on nonlinear optimal control theory during the later 60's naturally involved extentions and specialization of the available theoretical results (maximum principle and Hamilton-Jacobi-Bellman theory). In particular, our early research involved the full understanding of minimum-fuel optimal control (obviously motivated by satellite applications); the Ph.D. thesis by Gray [10] is an example of this line of research.

Another significant development was the derivation of the matrix-version of Pontryagin's maximum principle; see Athans [17]. The so-called "matrix minimum principle" made it very easy to examine a wide-variety of optimal control problems for which the control variables and state dynamics were most naturally expressed in matrix form, as is the case with several estimation problem; see Athans and Tse [19].

With the addition of Professors Sanjoy K. Mitter and Ian B. Rhodes to the faculty, the system theoretic manpower increased. The contribution by Mitter [37],[72], showed the generic interelationship between controllability and pole-assignment.

With respect to nonlinear estimation, the derivation of the extended Kalman filter and the second-order Gaussian filter by Athans et al [33] provided the algorithmic framework for more applied nonlinear state and parameter estimation studies in the years to follow.

Also in the late 60's a significant effort was mounted in understanding how to directly design nonlinear feedback controllers [57],[61]; this effort did not lead to any constructive answers, except that it taught us how hard is to design directly nonlinear feedback systems. In retrospect, these efforts were premature.

In the early seventies, the field was preoccupied by stochastic optimal control considerations. Part of these will be discussed in the Adaptive Systems and Large Scale Systems sections. However, some nice theoretical results were obtained by non-probabilistic approaches to uncertainty by Bertsekas and Rhodes [62],[74],[77] that pointed out, at least at an algorithmic level, the similarities and differences between probabilistic and set-theoretic models of uncertainty. A conscious decision was made not to get involved in the "fuzzy-set" approach to uncertainty advocated by Prof. Lotfi A. Zadeh.

The matrix minimum principle was used effectively to solve a class of stochastic optimization problems that simultaneously optimized, in a dynamic sense, control and measurement strategies; see Kramer and Athans [85],[87],[96],[108]. The class of problems were motivated by generic interception and rendezvous problems in which the on-board radar could switch waveforms to optimize the prediction accuracy associated with the target motion.

Multivalued performance criteria are generically important because is engineering designs one is commonly faced with conflicting objectives. The "Infimum Principle" by Geering and Athans [82],[99],[120] provided a theoretical tool for understanding the

class of optimization problems with several performance criteria that yield identical optimal solutions.

When Professor Alan S. Willsky joined the MIT faculty, and also became principal co-investigator of this grant, he spearheaded a research effort directed to estimation problems in classes of nonlinear systems; see Willsky and Marcus [106], [121],[127],[128],[129],[130],[134],[141]. Problems in satellite state estimation and phase-lock loops provided the motivation for this class of theoretical results.

In the mid 70's the emphasis was shifted into stochastic optimization problems with non-classical information patterns. Such problems are crucial in our fundamental understanding of decentralized control and large-scale system theory. Our NASA Ames grant monitor, Brian F. Doolin, provided encouragement to seek theoretical foundations for this class of problems. It was becoming obvious during that time-period that a microprocessor revolution was coming (did it ever!). From NASA's viewpoint one could see the need for decentralized and distributed control for large space structures and aircraft that became increasingly unstable and flexible. In addition to the research reported in the Large Scale Systems section, a significant effort was launched to understand these unconventional stochastic optimization problems. Key results can be found in the publications by Sandell and Athans [111],[139],[142],[145], in which a "finite state finite memory" maximum principle was developed; these results were valuable because they pointed out the tremendous increase in complexity that accompanies the decentralization of information. Along a different vein, the research of Chong and Athans [151] developed some periodic coordination mechanisms necessary to insure smooth operation of a decentralized control process.

By the late 70's the research under this grant on deterministic and stochastic control theory in the absence of a specific direction (i.e. large scale systems, adaptive control, geometric theory etc.) was slowly phased out. To a certain extent the general theoretical questions were well understood; also the computational shortcomings and difficulties were becoming apparent. Much of the grant emphasis shifted to failure detection, fault-tolerant control, robust linear control system design, and adaptive control.

Before we close-out this research area we would like to discuss some recent results on the robustness of nonlinear optimal full-state variable designs; see Tsitsiklis and Athans [253]. It was well-known since the early 60's that under suitable assumptions that the optimal feedback controller for nonlinear time-invariant systems, over an infinite time-horizon, led to a nominally stable design. From a technical point of view, the optimal cost-to-go, which satisfied a Hamilton-Jacobi-Bellman equation, could be used as a Lyapunov equation. What was not known, and that is the message of [253], that the resultant optimal control system is also <u>very robust</u>, in the sense that it has excellent multivariable gain and phase margins. Our on-going research under grant NASA/NAG 2-297 is actively exploiting this key consequence of optimality so as to develop a direct nonlinear control synthesis methodology.

1.5 Distributed Parameter Systems Theory

The research overviewed in the preceeding section dealt with optimal control and estimation theory for finite dimensional dynamical systems. Distributed parameter systems, i.e. systems that involve a time-delay and/or described by partial

differential equations, are of course very important. Our research on systems described by time-delays was motivated by remote interplanetary operations in which transmission delays are truly significant. Clearly, flexible aircraft and large space structures are inevitably described by certain types of partial differential equations.

Only a very limited portion of the grant resources was devoted to issues related to distributed parameter systems. This research was initiated when Prof. Mitter joined the faculty in the late 60's. The following publications fall in this category: [66],[94],[109],[131],[132],[133],[137],[143],[162].

The most significant developments in this area can be found in the Ph.D. thesis of T.L. Johnson [94], in the comprehensive monograph by Prof. S.K. Mitter [131],[132], [133], and in the Ph.D. thesis by Kwong [137]. For certain classes of distributed parameter systems we have a comprehensive understanding of the necessary theory for optimal estimation and control. However, we never had sufficient programming and computer resources to develop the necessary algorithms so as to carry out the necessary "feasibility studies" to test the advantages and limitations, if any, of the theoretical results. It is the author's hope that the availability of "free supercomputer time" to university researchers in the next few years will spark a renewed interest in this very important class of optimal estimation and control problems.

1.6 Adaptive Control Systems

The term "adaptive control" has been around at least since 1955 when Honeywell, Inc. designed the X-15 autopilot. In the ensuing 30 years adaptive control has captured the fancy of hundreds of control engineers and mathematicians, and at least one thousand papers and a dozen books have been devoted to the subject. One would

think that after so many years something solid, scientific, and practical would emerge. Unfortunately, in the author's opinion, the field of adaptive control remains confused, fragmented, and highly controversial. In spite of several noble efforts, a realistic generally-accepted definition, relevant formulation, and practical solution of the adaptive control problem is not available today.

For better or for worse, the research on adaptive control carried out under the auspices of this grant has had its own varied history. The author, in his role of principal investigator, was wary of mounting any concentrated attack on the adaptive control problem. However, every one of the several grant monitors inevitably (directly or in a subtle manner) posed the challenge "why don't you guys do something about adaptive control?" and their feelings were duplicated by respected colleagues and inquisitive graduate students. What happened is briefly described below.

The first phase of our adaptive control research started in the late 60's. During that time-period theoreticians viewed the then-popular adaptive schemes with disdain*. We decided to approach the adaptive control problem as a stochastic optimal control problem, in which the coefficients of the linear system were modeled as random variables, which could be estimated using an extended Kalman filter or second-order filter [33]. The Ph.D. thesis of Edison Tse [58] and subsequent papers by Tse and Athans [68],[69],[93], provided the initial framework. After Dr. Tse left MIT he collaborated at Systems Control Inc. with Dr. Yaakov Bar-Shalom and the original theoretical results in [58] were extended to a full blown theory of <u>dual-adaptive control</u> in a series of papers by Tse and Bar-Shalom in the mid 70's. See also [104].

There were several problems that existed with a pure stochastic control approach to the adaptive control problem. One major difficulty was that at each

* There were "adaptive algorithms" marketed by some companies that promised solutions to all control problems; they did nothing of the sort!

instant of time one had to propagate forward in time a matrix covariance equation and then solve, backward in time, a control Riccati matrix equation; so these schemes had extraordinary real-time computational requirements. Second, in the dual control problem one had to make several (clever) approximations to the solution of the nonlinear estimation and stochastic control problem, so there were no guarantees about optimality. Third, since one used a finite sliding horizon for the optimal control problem, it was next to impossible to make any precise statements about the global stability of the resultant control system. Finally, simulation results for "academic" problems showed that the adaptive control signal was highly oscillatory at the beginning of the adaptation period; such large chattering appeared bothersome (unfortunately, with the fixation of the field with state space models one never thought what these high frequency controls would do to excite unmodeled high-frequency dynamics in a practical setting).

Next, we decided to look for good signals for quick identification [116],[122], [144]. The theory told us that rapidly changing signals were good for identification, and that one could attribute the hunting behavior of the adaptive system as an attempt to identify the plant "quickly." Nonetheless, the equations looked too "messy" and we decided to abandon this line of research.

In the mid 70's we embarked upon the second phase of our adaptive control research; it still had a stochastic flavor to it and it was based upon some new theoretical results on open-loop stochastic dynamic hypothesis-testing*, coupled with an ad-hoc way of computing the adaptive control.

* These were called "partitioned algorithms" by D.G. Lainiotis. The author coined the term "Multiple-Model Adaptive Estimation (MMAE)" since it was more descriptive.

Dieter Willner's Ph.D. thesis [102] showed that the so-called Multiple-Model-Adaptive-Control (MMAC) was not optimal; however, simulations involving simple academic results showed promise. We then embarked upon an "applications-oriented" effort to try the MMAC on the NASA F-8C DFBW aircraft* [136].

From the F-8C study we found that the MMAC algorithm could do several strange things that we could not explain. Subsequent to the F-8C project we invested in two Ph.D. theses, one supported by this grant [179], to understand it; the MMAC algorithm defied understanding. So, further research along these lines was discontinued.

Meanwhile, the field of adaptive control was receiving increasing attention. In the mid 70's Prof. Astrom (Lund) proposed the self-tuning regulator (STURE), based on a simple minimum-variance scheme. The so-called Model Reference Adaptive Control (MRAC) scheme was shown to be globally asymptotically stable (under certain mathematical assumptions) by Prof. Narendra and his students (Yale) and Prof. Landau and his students (Grenoble). These adaptive schemes required much less computation than the stochastic dual control algorithms and the MMAC method. Furthermore, as we remarked above, the MRAC algorithm was proved to be stable, under certain assumptions. Using similar assumptions, Egardt (Lund) proved that the STURE algorithm was also globally stable.

In 1977 Dr. Gunter Stein of Honeywell joined the MIT EECS faculty as a part-time adjunct professor, and he became a most valuable contributor to the research carried out by this grant (see also Section 1.9). In addition, in 1979 Dr. Lena Valavani joined the MIT/LIDS research staff. Dr. Valavani's Ph.D. thesis at Yale, carried out

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*This effort was funded under a separate grant from the NASA Langley Research Center; Mr. Jarrell R. Elliott was the grant monitor. Ours was one of many parallel efforts, and labeled as the "most risky" by Mr. Elliott (how correct was his prediction!). The Honeywell design, headed by Dr. Gunter Stein, was labeled the most "conservative"; of course, it was the only one that, eventually, was successfully flight-tested at Dryden.

under the direction of Prof. Narendra, dealt with the theory and stability of MRAC algorithms. Her arrival was instrumental to the initiation of the third phase of our involvement in adaptive control.

This third phase of research on adaptive control under this grant is not over. Publications [217],[222],[224],[234],[237],[239],[241],[244], and [246] document the progress to date. Our research has shown, using a combination of theoretical analyses and simulation results, that the assumptions necessary to prove the global stability of the MRAC and STURE algorithms are always violated in practice due to the inevitable presence of high-frequency unmodeled dynamics (far-away stable poles, far-away non-minimum phase zeroes, small time-delays etc.). The combined effect of unmeasurable persistent disturbances and high-frequency unmodeled dynamics can result in instability of the closed-loop adaptive control system.

At present, we are studying the so-called Robust Adaptive Control Problem in which the presence of unmodeled dynamics and unmeasurable persistent disturbances is an integral part of the problem formulation. Since unmodeled dynamics can only be quantified by frequency-dependent bounds, the synthesis of robust adaptive algorithms appears to require real-time spectral calculations, e.g. Fast Fourier Transforms, in addition to the real-time solution of nonlinear differential equations. The problem formulation is realistic from a pragmatic viewpoint; however, it leads to several fundamental questions, in both robust adaptive estimation and control, that have not been considered in the literature.

1.7 Large Scale Systems

Research in large scale systems is directed primarily upon issues of decentralized and distributed control. Each controller is supposed to gather only a subset of the available sensor measurements and command only a subset of the available

controls. Some sort of a coordination mechanism may be necessary to ensure that this decentralized approach to control will "work well." Such coordination mechanisms require real-time communications. Hence, one cannot separate the decentralized system performance from the intra-controller communications requirements. Therefore, architectural issues are an integral part of large scale system theory and practice.

The powerful theoretical optimal estimation and control tools (maximum principle, dynamic programming, Kalman filtering, etc.) are <u>centralized theories</u>. Unfortunately, over the 18 years spanned by this grant we have not been able to generate new powerful theories that reduce the decentralized control problem to a routine status; to the best of our knowledge no other research group has had much success either.

It is not too difficult to figure out that the major difficulty in decentralized control theory revolves around the fact that each controller has different information. This is called "a non-classical information pattern" or "non-nested" information. Even in a cooperative team or cooperative multi-person formulation, the existence of "private" information leads to several unresolved issues that contribute to immense theoretical difficulties.

When we started our research on large scale systems around 1969, with the advise and consent of our NASA Ames grant monitor Brian F. Doolin, the only "storm warnings" about the difficulty associated with non-classical information patterns was due to the famous Witsenhausen counterexample [1968] which demonstrated that a simple discrete-time LQG problem, whose solution is trivial in the centralized case, became an almost impossible problem when the information structure was non-classical.

One line of inquiry, led by Professor Ian B. Rhodes, was directed toward the use of game-theoretic concepts extended to the dynamic case (differential games) to capture the multi-controller nature of decentralized control systems [43],[51], [52],[53],[149]. This line of research demonstrated the complexity issues introduced by the presence of multiple decision-makers in the decentralized control problem. However, it did not directly address the issues associated with non-classical information pattern.

Along a more pragmatic vein, one can suspect that there are two classes of problems in which the decomposition of a centralized design into a decentralized design should be "easy".

(1) Weakly coupled systems, in which the dynamic interactions between individual subsystems are "small". Ordinary perturbation techniques can be used to study dynamic systems that reflect such weak-coupling phenomena.

(2) Systems with significant time-scale separation, i.e. with different bandwidths. For such systems one can take advantage of the bandwidth separation to decompose the centralized controller. Singular perturbation theory can be used to study dynamic systems that exhibit the time-scale separation property.

In the early 70's Chong, Kwong, Athans, and Sandell studied the case of weakly coupled systems [88],[95],[103],[124],[139],[151] using the LQG framework. This line of research developed the necessary methodology for designing decentralized LQG systems, whose performance approached that of the centralized design as the degree of dynamic coupling among the subsystems became smaller and smaller.

In the mid 70's Sandell and Teneketzis developed the theoretical framework and design methodology for exploiting time-scale separation so as to suitably decompose LQG-based centralized designs [148],[158],[159],[168]. Once more the performance of this type of decentralized design would approach that of the centralized one as the bandwidth separation became larger and larger.

These two lines of inquiry pretty much completed the "easy" cases of decentralized control. In both cases, the impact of a non-classical information pattern is minimal, since each subsystem had "enough" information to result in to superior performance, and the requirements of intra-system communication were minimal.

The "hard" problems of decentralized control theory remained [111],[124],[139],[142],[170]. A notable achievement is contained in the Ph.D. thesis by Sandell [111] in which the complexities of non-classical information structure upon decentralized control were confronted. Although one could derive a maximum-principle type of theorem for this class of problems, the computational difficulties are immense.

Decentralized control theory research continued as an active research area although it was not supported by this NASA grant. However, significant contributions are few and rare. It is unlikely that we are going to see one or two new theorems that will bring a revolutionary change in the way engineers design decentralized control systems (in an ad-hoc manner). The relevant theoretical questions change drastically with the type of physical application that one has in mind. This might suggest that a purely abstract normative theory, based on stochastic optimization, for decentralized decision problems may be an almost impossible goal. Indeed recent results by Prof. John N. Tsitsiklis suggest that such optimal distributed decision problems belong to the class of NP-complete problems, which are notorious for their

combinatorial complexity. Therefore, one must be satisfied with more ad-hoc approaches to decentralized control; such ad-hoc approaches must necessarily be guided by the specific application at hand.

1.8 Failure-Detection and Fault-Tolerant Control

Advances in microprocessor technology during the early 70's provided the control engineer with the ability to monitor in real-time several signals in the control loop so as to quickly and reliably carry out the function of Failure Detection and Identification (FDI). From an aerospace perspective, as aircraft became increasingly statically unstable and more flexible, the flight control system designer had to worry about flight critical sensors and actuators, and their level of redundancy.

Our NASA Ames Research Center grant monitor, Mr. Brian F. Doolin suggested that we devote part of the grant resources to study important issues in reliability and dynamic systems which included sensor FDI, actuator FDI, and fault-tolerant control theory in general.*

The major prime-mover of the research on FDI was Professor Alan S. Willsky who joined the MIT faculty in 1974 and became co-principal investigator of this grant. Professor Willsky and his students have obtained a great variety of results in the FDI area; see publications [135],[155],[156],[203],[204],[209],[220],[223],[230],[233 [240],[247],[248],[251], and [252]. Indeed many of the theoretical results and algorithms for FDI have been used quickly by industry and have been flight tested; the Generalized Likelihood Ratio (GLR) test is the prime example.

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*Also, starting in 1976, NASA Langley Research Center funded us to study the underlying theory of sensor FDI. Eventually, in 1981, the financial support of both Ames and Langley Research Centers were consolidated within this grant.

The early results on designing FDI systems are summarized in the classic survey paper by Willsky [156] which was published in 1976. Subsequent research efforts in this area can be best characterized by robust FDI which attempts to quantify dynamic system model errors and their impact upon FDI algorithms. Key results can be found in the Ph.D. thesis of Chow [203] and subsequent publications by Chow and Willsky [204],[209],[223],[230]. Another set of important results, relying on the projection method and parity tests, were obtained by Lou in his thesis [220]; these have led to a variety of extentions and modifications for robust FDI [223],[240],[247],[251],[252]. The recent paper by Willsky [248] contains a summary of the more recent results.

The vast majority of the FDI theory and algorithms apply in an "open-loop" monitoring context. They are a necessary, but by no means sufficient, ingredient of any fault-tolerant design. Clearly, following the identification and isolation of any failure it may be necessary to <u>reconfigure</u> or <u>restructure</u> the feedback control system. Our research on fault-tolerant control was the first attempt to apply stochastic optimal control theory (see Section 1.4) to address fault-tolerant control. Publications [172],[187],[188],[199], and [228] document our research findings in the fault-tolerant control area.

The Ph.D theses of Birdwell [172] and of Chizeck [228] contain the bulk of the available results. We modeled failures as probabilistic transitions of appropriate parameters from one set of values to another; these were modeled as discrete Markov chains. These discrete transitions then impacted the dynamic evolution of stochastic state and measurement equations. This model yielded a "hybrid" state-space; some states were discrete, while others were continuous. An optimal stochastic LQG framework was adopted for the fault-tolerant design. Indeed, from a mathematical

point of view, the formulation was similar to that of a stochastic adaptive control problem (see Section 1.6). There were three sources of uncertainty

(1) The probabilistic transitions of the discrete-valued states, modeling failures

(2) The process noise, modeling system disturbances

(3) The measurement noise, modeling sensor errors.

In general, one cannot derive the solution of the stochastic optimal control problem when all three uncertainties are present simultaneously. The publications by Birdwell _et al_ [172],[187] concentrate upon full state measurements (with no errors) and zero-process noise. The onset of "failures" is infered (with some delay) by the measurement of the state variables. In this case, one can solve the stochastic optimal control problem with or without reconfiguring the control system. However, the solution is characterized by an extremely complex set of coupled Riccati difference equations. It was next to impossible to deduce any guaranteed stability results.

In the publications by Chizeck _et al_ [188],[199],[228] it was assumed that the failure induced transitions could be sensed separately and instanteneously, by a "super" FDI system, and their impact upon the stochastic optimal control problem analyzed. Once more the equations are very complex, and only limited insight into the stability of the fault-tolerant control system can be obtained.

The design of fault-tolerant control systems, and restructurable flight control systems in particular, remains an active research area of interest to NASA. Given the complexities, discussed above, associated with an optimal control approach to the problem, more pragmatic applications-dependent approaches must be tried out and evaluated.

1.9 Multivariable Linear Feedback Control Systems

Throughout the long history of this grant the development of unified design methodologies for linear multivariable feedback control systems has been an un-interupted and persistent research objective. With very few exceptions, we focused our approach to several variants of the Linear-Quadratic (LQ) and Linear-Quadratic-Gaussian (LQG) design methodology. Indeed the MIT/LIDS control group has been closely identified with LQG-based designs. Happily, LQG-based designs have led to a systematic design methodology for multivariable servomechanisms, using an intergrated state-space and frequency-domain framework; the so-called LQG/LTR approach.

Our long-term commitment to LQ and LQG based designs can be evidenced by the large number (52) of publications that fall in this category. These are: [5],[16], [22],[26],[27],[31],[34],[41],[42],[59],[64],[67],[81],[83],[86],[89],[91],[97],[98], [101],[110],[112],[113],[123],[125],[140],[146],[147],[153],[154],[161],[163],[169], [173],[176],[178],[180],[190],[193],[194],[201],[206],[207],[210],[214],[216],[242], [243],[249],[256], and [257]. These publications exclude "feasibility studies," as well as the adaptation of the LQG methodology for adaptive systems, large-scale systems, fault-tolerant control, and numerical algorithms.

During the late 60's most of the attention was focused upon certain variants of the time-varying LQ problem. The development of techniques by Kleinman et al for approximating the time-varying control gains by piecewise constant ones was reported in [5],[16],[26],[31]. The correct formulation and solution of the LQ sampled data problem, in which the sampling function imposed piecewise constant constraints on the control, was developed by Levis [27]. A series of publications by Levine and Athans [34],[41],[42],[59],[89] solved the so-called "output feedback" or "limited

state feedback" problem, in the absence of dynamic compensation; these ideas were, and still are, used extensively in the aerospace applications literature. The ideas behind output feedback were also used by Johnson and Athans for the design of limited-order dynamic compensators [67],[89]. A summary of the LQG methodology and its potential for multivariable feedback design was given in [86] in 1971.

During the early 70's the limitations of LQ/LQG regulators in the context of command-following and disturbance-rejection servomechanisms problems was becoming apparent. Athans and Sandell showed how to properly formulate LQ problems so that integrators are introduced in the control loop resulting in zero steady-state errors for step command inputs and constant disturbances [81],[83],[91],[98]. A series of papers by Platzman et al and Blanvillain et al attempted to overcome some of the dimensionality problems of LQG compensators [97],[101],[110],[123],[153],[154],[173],[178],[190]. The introduction of the first 4-bit and 8-bit microprocessors influenced this line of research.

A significant (in retrospect) turn of events occured during the mid 70's which eventually led to the integrated time-domain and frequency-domain methodology of the LQG/LTR method, and the introduction of stability-robustness considerations in MIMO servomechanism design. The author, in 1973, participated in a consulting capacity in an LQ-based design for the control of the Trident submarine (the report is classified). In this design, disturbances of large magnitude would saturate one of the control surfaces; while the control surface remained saturated the submarine exhibited short-term oscillatory behavior. Since control saturation can be interpreted

as a downward gain margin, it became apparent that nothing was known about the MIMO gain and phase margin properties of LQ and LQG designs.* A decision was made to initiate research to understand multivariable gain and phase margins. This change in research directions was encouraged by Mr. Brian F. Doolin, our NASA/Ames grant monitor during that time period; indeed it was within the theme of reliable and robust control system design (see also Section 1.8) that dominated our research during that time period.

The first set of MIMO robustness results were obtained by P.K. Wong in his S.B. and S.M. thesis; he proved that multivariable LQ regulator designs have a guaranteed infinite upward gain margin and 50% (6 db) downward gain-reduction margin in each control channel independently and simultaneously; see [112],[140],[161]. The gain margin results were quickly generalized by Safonov in his Ph.D. thesis. to include the guaranteed $\pm 60°$ phase margin properties. Indeed, from a chronological point of view, Safonov developed the conic-sector stability theory (see Section 1.3) motivated by the need for more elegant and general proofs for his multivariable gain and phase-margin results; see [146],[163],[169],[180],[201].

Adopting a historical perspective, the results on multivariable robustness obtained by Safonov represent a truly significant turning point in multivariable control system theory and engineering. At about the same time, the addition in the mid 70's of Dr. Gunter Stein of Honeywell Systems Research (SRC) to the MIT faculty as an Adjunct Professor of Electrical Engineering (part-time) was also a notable event. Stein's commitment "to make modern control theory practical" had far reaching implications for the research and educational activities of the author, the MIT/LIDS

*In the SISO case the 1963 classic paper of R.E. Kalman, "When is a Linear System Optimal" pinpointed the guaranteed robustness properties of LQ regulators.

control group, and the field of modern control engineering. I must also point out the instanteneous cooperation of Brian F. Doolin who gave me at once the green light to support the MIT portion of Dr. Stein's research under this grant, and did the necessary administrative paperwork so that our research could proceed smoothly.

The years 1977-1979 were truly exciting ones at MIT. Professors Stein, Sandell, Laub and the author, together with a fine crew of students concentrated upon the key robustness issues. There was also improved lines of communication between MIT/LIDS and the fine research group at Honeywell SRC.* And many good things happened rapidly.

The use of singular values for MIMO control systems (generally credited to Doyle) was adapted to place Safonov's general stability-robustness results in a more concrete setting; under this grant relevant research on stability-robustness and its use in LQ-base designs can be found in [176],[185],[193],[194],[207],[214],[249], culminating in the doctoral thesis of N.A. Lehtomaki [210].

At a more general vein, G. Stein was the driving force behind the integration of frequency-domain and state-space concepts for multivariable servomechanism synthesis, and the development of the so-called LQG/LTR design methodology; see [206],[207],[210], [216],[243],[256],[257]. The theory behind the LQG/LTR design methodology for MIMO servos, and the accumulated pragmatic understanding of its advantages and limitations (see Section 1.12), have resulted in a valuable body of knowledge that will undoubtedly impact the engineering design of complex multivariable feedback control systems in the decades to come.

The general understanding of how LQG/LTR control systems work, coupled with the nonlinear robustness results of Tsitsiklis and Athans [253], have provided, for the

*One of the students was John C. Doyle who completed an S.B. thesis under the direction of Prof. Sandell and an S.M. thesis under the direction of Prof. Mitter. J.C. Doyle left MIT (to get away from all this LQG stuff) and became a consultant to Honeywell SRC and a graduate student at U.C. at Berkeley. He did not quite forget LQG; see [206].

most part, motivation for our direct nonlinear system synthesis studies carried out under the follow-on grant, NAG 2-297.

1.10 Space Systems Studies

Our feasibility studies related to attitude control and similar satellite related problems were instigated during the late 60's at the suggestion of our NASA/ERC grant monitor, Dr. George Kovatch. The following publications are classified in this category: [3],[4],[10],[15],[39],[106],[160].

Most of these quasi-applied studies were carried out in parallel with our theoretical refinements related to minimum-fuel optimal control systems as reported in Section 1.4. These feasibility studies provided us with a better understanding of pragmatic issues related to minimum-fuel attitude control and minimum-fuel orbital transfer.

When the grant was transfered from NASA/ERC to NASA/Ames these studies were deemphasized in favor of feasibility studies involving air traffic control and aircraft systems.

At any rate, what we found is that most interesting fuel-optimal problems for nonlinear systems, and in particular for orbit-transfer types of optimization problems, required reliable numerical techniques for solving the so-called singular optimal control problem. Other researchers have proposed in the mean-time several approaches for solving optimal control problems involving singular arcs; our experience [32] has been that these methods can be extremely ill-conditioned from a numerical point of view. It is the author's opinion that the reliable computation of optimal control problems with singular arcs is still an open research problem.

1.11 Air Traffic Control Studies

Our interest in air traffic control spans the time period from 1969-1975. When this grant was transfered to the NASA Ames Research Center, our limited involvement with air traffic control studies was motivated by the pioneering work of Dr. Heinz Erzberger and his colleagues at NASA/Ames on the application of optimal control theory to air traffic control problems. The following publications represent a summary of our efforts in the air traffic control area; [50],[60],[70],[79],[84],[90],[119],[138].

The research was carried out primarily by three S.M. students: L.W. Porter, A.H. Sarris, and F.M. Lax. The work progressed from 2-D, to 3-D, to 4-D versions of the air traffic control problem. It represented some challenging applications of deterministic optimal control theory coupled with heuristics.

We had a lot of interesting discussions with Dr. Erzberger and his colleagues at NASA/Ames about air traffic control. Perhaps our very limited research had some impact on their thinking; I tend to doubt it. Dr. Erzberger and his colleagues certainly knew the state-of-the-art in optimal control theory, and were most competent to apply it to several aspects of the air traffic control problem and to aircraft trajectory optimization as their present results have clearly demonstrated.

1.12 Aircraft Systems Studies

With the transition of the grant from NASA/ERC to NASA/Ames, and later on with the consolidation of both Ames and Langley funding under the same grant, our "feasibility studies" shifted from space-oriented problems to aircraft oriented problems, including engines. Apart from our adaptive control studies on the F-8C

aircraft (see Section 1.6) and air traffic control studies (see Section 1.11), the following publications represent our research contributions in the aircraft systems area: [47],[80],[126],[195],[198],[215],[219],[221],[227],[231],[235],[245],[254],[255].

These feasibility studies were primarily carried out by S.M. students. The idea was to evaluate the advantages and limitations of existing control systems design methodologies, and of the LQ and LQG methodologies in particular, in a more pragmatic and realistic setting. In this manner, we gained additional insight into the proper use of the theory, and based upon the conclusions pose other theoretical directions to overcome the limitations, or boundaries, of existing theory. All of the specific problems were selected jointly with our NASA Ames (Brian F. Doolin, Luigi Cicolani, George Meyer) and Langley (Jarrell R. Elliott) grant monitors in support of on-going NASA research projects.

The first class of aircraft related studies were carried out by T.L. Johnson _et al_, and were the outgrowth of a cooperative program with Honeywell. The problems were motivated by large aircraft (such as the B-52 and C-5A) where flexure motion of the wings was a significant problem; see [47],[80],[227]. This provided us with valuable insight into pragmatic issues of controlling an essentially distributed parameter system (a bending wing), including sensor and actuator locations, and motivated some of the basic research on distributed parameter systems (see Section 1.5).

In the late 70's NASA/Ames initiated a program in support of the U.S. Navy efforts to land V/STOL aircraft on small platforms such as the DD-963 class destroyer. The research by McMuldroch, Bodson _et al_ was directed upon this problem;

see [195],[198],[215],[219],[221],[231]. In this case, we not only had to study the dynamics of the VTOL aircraft but we had to develop detailed models of the pitch, heave, roll, and sway motions of the DD-963 at high sea states. We developed both "chase-the-deck" and "landing-on-a-peak" control strategies.

During the past few years our feasibility studies were driven by the growing interest in integrated aerodynamic and propulsion control; this requires truly multivariable coordinated control of the aircraft control surfaces and modern turbofan engine fuel and geometry variables. In addition to their obvious importance from an applications standpoint, these feasibility studies have been serving a very useful purpose in understanding the power of the LQG/LTR design methodology (see Section 1.9). Studies include the longitudinal control of the Harrier AV-8A aircraft [235],[244] using the elevator, thrust, and nozzle angle as control variables; also the multivariable control of the F-100 engine [245],[255].

1.13 Digital Implementation Issues

As digital fly-by-wire systems progressed from a dream to reality, and as the microprocessor revolution has changed the rules of practical design, increasing attention was paid to the specific new design issues associated with digital compensators.

One line of investigation was pursued by Prof. T. Johnson and his students; [167],[175],[184]. These related to explicit incorporation of the finite-state nature of digital arithmetic in the design of digital compensators for estimation and control.

A different line of investigation was pursued by Moroney et al; [196],[200], [212],[213] in which roundoff noise, finite-wordlength, scaling, and architectural issues related to microprocessor-based compensators were analyzed.

A third line of inquiry was developed by Thompson et al [226],[242]. In this research the conic sector results of Safonov [169] were used to study performance and robustness issues in sampled-data systems which consist of a continuous-time plant controlled by a digital computer. Since the digital sampling process results in a time-varying system (from a continuous-time point of view), the conic sector "center" was used to define a time invariant operator, while the conic sector radius bounded the impact of time-variations by a time invariant bound.

1.14 Numerical Methods

From the very inception of this grant, as can be evidenced by the first publication [1], a portion of the grant resources were directed toward the development of numerical algorithms and research software which provided the MIT/LIDS control group the capability to carry out number crunching in support of our feasibility studies, and contributing to the generation of new algorithms that could be used by the control science and engineering community at large. The research along these lines is reported in publications [1],[5],[10],[28],[44],[49],[55],[76],[105],[114],[150],[152],[185], [191],[194].

Non-differentiable static and dynamic optimization problems arise naturally in a vast and wide variety of applications. Along these lines we single out the key contributions by Mitter and Bertsekas [76],[105] and by Hager and Mitter [152]; these had significant impact on subsequent algorithmic design.

The numerical solution of the two-point-boundary value (TPBV) problem received quite a bit of attention during the early phases of this grant. Such two-point-boundary-value problems arise inevitably when one derives the necessary conditions implied by Pontryagin's maximum principle. Publications [10],[28] deal with the adaptation of Newton's method to compute fuel-optimal controls. In a more general setting, the numerical solution of TPBV problems is addressed in [49].

For LQ, LQG, and Kalman filter designs one needs, of course, to solve the so-called algebraic Riccati equation (ARE). In [1] this was obtained by brute-force numerical integration of the associated matrix differential equation. In [5] Kleinman developed the so-called "Kleinman method" which used Newton's method to calculate the solution to the ARE; see also [114]*.

When the singular value decomposition method was developed in the late 70's, critical issues regarding their computations were addressed by Alan J. Laub [185], [194]. His results represent essential features of all reliable present-day commercial and propitiatory software packages for MIMO control system analysis and design.

1.15 Concluding Remarks

The author has attempted to provide a guided tour of the nature of the research conducted at MIT/LIDS with financial support derived under this NASA grant. One really cannot do justice to the immense volume of results obtained over the past 18 years. This does require reading of the cited publications.

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*"Kleinmans method" was, and still is, used extensively in many software packages; it does not work very well when the eigenvalues are far spread. Its main competitor was "Potter's method" which does not work very well when the eigenvalues are close together Only during the late 70's, when Alan J. Laub produced more reliable means for solving the ARE, these methods became technologically obsolete.

At the very least, it is the author's hope that he illustrated the nature of the interactions that have taken place between the MIT/LIDS group and the NASA Electronics, Ames and Langley Research Centers. It has been a mutually rewarding experience and due credit must be given to the various NASA leaders that served as grant monitors over the years: George Kovatch, Brian Doolin, Luigi Cicolani, Jerry Elliott, and George Meyer. Their encouragement, suggestions, criticisms, and support were in the long run much more valuable than the dollars that NASA provided to MIT. How they managed to fight the inevitable "budget battles" and continue uninterrupted support for 18 years is beyond my comprehension!

2. PUBLICATIONS

In this section we present the list of publications that document the research conducted under NASA grant NGL-22-009-124 from 1966 to 1984. A total of 257 reports, theses, conference and journal articles are included. The listing is in roughly chronological order.

A remark about the list of publications is in order. Every effort has been made to eliminate duplication of similar material. This is particularly true of papers that are published in refereed journals. These start as preprints, revised preprints, often appear in conference proceeding volumes, and eventually (after 2-3 years) they are published in archival journals. The contract monitors have received all these versions of the paper. However, for this final report, we have eliminated all prior versions of a particular journal article. Thus, the publications list is not "padded". Also we have not included the semi-annual status reports submitted to satisfy the contractual requirements.

Each one of the publications listed below acknowledges this NASA grant. Several publications also acknowledge other sources of support. We have not made any attempt to "flag" these joint-support publications in the list that follows.

1. M. Athans and W.S. Levine, "On the Numerical Solution of the Matrix Riccati Differential Equation Using a Runge-Kutta Scheme," Electronic Systems Laboratory Report 276, M.I.T., 1966.

2. M. Athans, "On the Uniqueness of the Extremal Controls for a Class of Minimum Fuel Problems," IEEE Transactions on Automatic Control, Vol. AC-11, No. 4, October 1966, pp. 660-668.

3. S. Greenberg, "Minimum Time and Fuel Trajectories for Orbital Transfer," Electronic Systems Laboratory Report No. 290, M.I.T., December 1966.

4. S. Greenberg and M. Athans, "On Minimum Time and Fuel Orbital Transfer," Proc. NEC, Chicago, Illinois, Vol. 23, pp. 98-101, 1967.

5. D.L. Kleinman, "Suboptimal Design of Linear Regulator Systems Subject to Computer Storage Limitations," Electronic Systems Laboratory Report 297, M.I.T., February 1967.

6. M. Athans and F.C. Schweppe, "On Optimal Waveform Design via Control Theoretic Concepts," Information and Control, Vol. 10, April 1967, pp. 335-377.

7. R.W. Brockett, "An Inverse Function Theorem with Application in Signal Processing and Optimal Control," Internal Memorandum, Electronic Systems Laboratory, M.I.T. April, 1967.

8. J.C. Willems and M. Gruber, "Comments on a Combined Frequency-Time Domain Stability Criterion for Autonomous Continuous Systems," IEEE Trans. on Auto. Control, Vol. AC-12, April 1967.

9. R.W. Brockett and H.B. Lee, "Frequency Domain Instability Criteria for Nonlinear and Time-Varying Systems," Proceeding of the IEEE, May 1967.

10. D.L. Gray, "Computation of Approximate Fuel Optimal Control," M.I.T. Electronic Systems Laboratory, Report ESL-R-307, May, 1967, Cambridge, MA.

11. E. Tse, "Application of Pontryagin's Minimum Principle in Filtering Problems," M.S. Thesis, Dept. of E.E., Cambridge, MA. May 1967.

12. A. Debs, "On Optimal Nonlinear Feedback Control," IEEE Transactions on Automatic Control, Vol. AC-12, pp. 329-331, June 1967.

13. E. Noldus, Oscillations in a Simple Nonlinear Feedback Systems, S.M. thesis, Dept. of Electrical Engineering, M.I.T., June 25, 1967.

14. R.W. Brockett, "A Note on Positive Operators-I," Internal Memorandum, Electronic Systems Laboratory, M.I.T., July 1967.

15. D.L. Gray and M. Athans, "Attitude Control of a Satellite in Circular Orbit," Proc. 2nd IFAC Symposium on Automatic Control in Space, Vienna, Austria, Sept. 1967.

16. T. Fortmann, "Optimal Piecewise Constant Solutions of the Linear Regulator Problem," M.I.T. Electronic Systems Lab., Report ESL-R-326, October 1967.

17. M. Athans, "The Matrix Minimum Principle," Information and Control, Vol. 11, Nov. 1967, pp. 592-606.

18. M. Athans, "The Relationship of Alternate State-Space Representation in Linear Filtering Problems," IEEE Trans. on Automatic Control, Vol. AC-12, No. 6, Dec. 1967, pp. 775-776.

19. M. Athans and E. Tse, "A Direct Derivation of the Optimal Linear Filter Using the Maximum Principle," IEEE Trans. on Automatic Control, Vol. AC-12, No. 6, December 1967, pp. 690-698.

20. W.S. Levine, "On the Optimization of Decoupling Feedback," Report for NASA/ERC, December 1967.

21. M. Gruber, "Stability Analysis Using Exact Differentials," Ph.D. Thesis Proposal, Dept. of E.E., M.I.T., ESL-TM-369, 1968.

22. A. Levis and M. Athans, "Sampled-Data Control of High Speed Trains," M.I.T. Electronic Systems Lab., Report ESL-R-339, January 1968.

23. R.W. Brockett, "Related Problems in Approximation Theory and Optimal Control," Proceedings of the 1968 Princeton Conference on Information Theory and Systems Science, March 1968.

24. J. Burchfiel and M. Athans, "Design of Transmission Lines and Waveguides by the Distributed Maximum Principle," Proc. 2nd Annual Princeton Conf. on Information Sciences and Systems, pp. 257-263, March 1968.

25. E. Tse, "On the Utility of Information in System Problems," Control Theory Group, Research Note 1968-1, M.I.T., March 1968.

26. M. Athans and D.L. Kleinman, "The Design of Suboptimal Linear Time-Varying Systems," IEEE Trans. Auto. Control, Vol. AC-13, pp. 150-159, April 1968.

27. A. Levis, "On the Optimal Sampled-Data Control of Linear Processes," Ph.D. Thesis, Dept. of Mechanical Eng., M.I.T., May 1968.

28. D.L. Gray and M. Athans, "Computation of Fuel Optimal Controls via Newton's Method," Preprints 1968 JACC, Ann Arbor, Michigan, pp. 946-961, June 1968.

29. R.A. Skoog, "On the Stability of Pulse-Width Modulated Feedback Systems," Proc. 1968 JACC, Ann Arbor, Michigan, pp. 152-161, June 1968.

30. J.C. Willems, "Nonlinear Harmonic Analysis," ESL-TM-357, MIT, July 1968.

31. D.L. Kleinman, T. Fortman, and M. Athans, "On the Design of Linear Systems with Piecewise Constant Gains," IEEE Trans. on Automatic Control, Vol. AC-13, pp. 354-361, August 1968.

32. L.C. Kramer, "On Singular Solutions in Optimal Control Problems," S.M. Thesis, Dept. of Electrical Engineering, M.I.T., September 1968.

33. M. Athans, R.P. Wishner, and A. Bertolini, "Suboptimal State Estimation for Continuous Time Nonlinear Systems from Discrete Noisy Measurements," IEEE Trans. on Automatic Control, Vol. AC-13, No. 5, October 1968, pp. 504-514.

34. W.S. Levine and M. Athans, "On the Design of Optimal Linear Systems Using Only Output-Variable Feedback," Proc. 1968 Allerton Conference, Monticello, ILL., October 1968, pp. 661-670.

35. E. Tse, "Generalized Random Processes," M.I.T., Electronic Systems Laboratory Report ESL-R-366, October 1968.

36. J.C. Willems and R.W. Brockett, "Some New Rearrangement Inequalities Having Application in Stability Analysis," IEEE Trans. Auto. Control, Vol. AC-13, pp. 539-549, October 1968.

37. S.K. Mitter, "A Result for Linear Systems Defined Over Arbitrary Fields: Equivalence of Controllability and Pole Assignment," Proceedings of the 7th Annual Allerton Conf. on Circuit and Systems Theory, 1969, pp. 396-398.

38. J.C. Willems, "A Survey of Stability of Distributed Parameter Systems," Proc. 1969 JACC, Boulder, Colorado, pp. 63-101.

39. M. Athans, and A.S. Debs, "On the Optimal Angular Velocity Control of Asymetrical Space Vehicles," IEEE Trans. of Auto. Control, Vol. AC-14, Feb. 1969, pp. 80-83.

40. A.S. Debs, "Optimal and Suboptimal Feedback Control for Deterministic Systems," Ph.D. Thesis, Dept. of Elec. Eng., M.I.T. February 1969, also M.I.T. Electronic Systems Laboratory Report ESL-TM-375, February 1969.

41. W.S. Levine, "Optimal Output-Feedback Controllers for Linear Systems," Ph.D. Thesis, Dept. of Elec. Eng., M.I.T. February 1969, also M.I.T., Electronic Systems Laboratory Report ESL-R-374, February 1969.

42. W.S. Levine, and M. Athans, "Average-Optimal Output-Feedback Controllers for Linear Time-Varying Systems," M.I.T. Electronic Systems Laboratory, Paper No. ESL-P-377, February 1969.

43. I.B. Rhodes, and D.G. Luenberger, "Differential Games with Imperfect State Information," IEEE Trans. on Auto. Control, AC-14, No. 1, February 1969.

44. K. Sorensen, "A Conjugate Gradient Method for Calculating Constant-Parameter Sub-optimal Control," M.S. Thesis, February 1969.

45. G.L. Blankenship and R.A. Skoog, "Loop Gain Stability Criteria for Pulse-Width-Modulated Feedback Systems," Internal Memorandum, March 17, 1969.

46. M. Athans, A.D. Debs, K.M. Joseph, "On Approximation of Function, Topological Mappings and Nonlinear Feedback Control Systems," ESL-R-389, June 1969.

47. T.L. Johnson, "The Aerodynamic Sunface Location Problem in Optimal Control of Flexible Aircraft," S.M. Thesis and ESL-R-387, MIT, June 1969.

48. T.E. Fortmann, "Optimal Design of Filters & Signals Subject to Sidelobe Constraints," Ph.D. Thesis and ESL-R-400, MIT, September 1969.

49. H.P. Geering, "Two Point Boundary Value Problems in Optimal Control," M.S. Thesis, Department of Electrical Engineering, M.I.T., Cambridge, Mass., September 1969.

50. L.W. Porter, "On Optimal Scheduling and Holding Strategies for the Air Traffic Control Problem," M.S. Thesis, ESL-R-401, September 1969.

51. I.B. Rhodes, "On Nonzero Sum Differential Games with Quadratic Cost Functions," Proc. First International Conference on Differential Games, Amherst, Mass., September 1969.

52. I.N. Rhodes and I.B. Chammas, "Nonzero-Sum Linear Differential Games," First International Conference on the Theory and Applications of Differential Games, September 1969.

53. I.B. Rhodes and D.G. Luenberger, "Stochastic Differential Games with Constrained State Estimators," IEEE Trans. Auto. Control, Vol. AC-14, pp. 476-481, October 1969.

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3. PEOPLE

In this section we summarize the career paths of several of the contributors to the research carried out under NASA grant NGL-22-009-124. All information may not be completely up to date.

Over the years 16 MIT faculty and post-doctoral fellows have received partial support from this grant and have contributed to the research as documented in the publications section. The names appear in roughly chronological order as reflected in the time frame of the appearance of the publications that document the research.

One of the most extraordinary statistics, however, is reflected in the total number of Ph.D. students that have received full or partial support from this grant. A total of 51 Ph.D. students (5 of whom are still in different stages of their doctoral research at MIT) received support from this grant. Even more gratifying is that the vast majority of these students have distinguished positions in universities and industry; the list of names appears to be like "who-is-who" in control science and engineering.

M. ATHANS is a faculty member at MIT in the EECS department. He has been the Principle Investigator of this grant since its inception.

R.W. BROCKETT was a faculty member at MIT. He then joined the faculty at Harvard University.

W.S. LEVINE, after receiving his Ph.D. from MIT, joined the EE faculty at the University of Maryland.

S. G. GREENBERG, after receiving his Ph.D. from MIT, joined IBM, then TASC, and he is now a manager with Digital Equipment Corp.

F.C. SCHWEPPE is a faculty member at MIT in the EECS department.

D.L. KLEINMAN, after receiving his Ph.D. from MIT, joined Bolt, Beranek, and Newman Inc., and then Systems Control Inc. He is now a faculty member in the EECS department at the Univ. of Connecticut.

J.C. WILLEMS, after receiving his Ph.D. from MIT, joined the MIT faculty and then went to the University of Groningen, Holland.

M. GRUBER, after receiving his Ph.D. from MIT, joined the staff of the MIT Lincoln Laboratory.

D.L. GRAY, after receiving his Ph.D. from MIT, joined the NASA Electronic Research Center. Later he went to Aerojet Corp.

E. TSE, after receiving his Ph.D. from MIT, joined Systems Control Inc. He is now a faculty member at Stanford University in the Engineering-Economics department.

A. DEBS, after receiving his Ph.D. from MIT, joined Systems Control Inc. He is now a faculty member at Georgia Institute of Technology in the EE department.

T. FORTMANN, after receiving his Ph.D. from MIT, joined the faculty of Newcastle University in Australia. He is now at Bolt Beranek and Newman, Inc.

A. LEVIS, after receiving his Ph.D. from MIT, joined the EE faculty at Brooklyn Polytechnic Institute and then Systems Control Inc. He is now Senior Research Scientist in LIDS at MIT.

J. BURCHFIEL, after receiving his Ph.D. from MIT, joined Bolt, Beranek, and Newman Inc.

R.A. SKOOG, after receiving his Ph.D. from MIT, joined Bell Telephone Laboratories, Inc.

L.C. KRAMER, after receiving his Ph.D. from MIT, joined the MIT Lincoln Laboratory. He is now with ALPHATECH Inc.

S.K. MITTER, is a member of the MIT faculty in the EECS department.

I.B. RHODES, was a faculty member at MIT. He is now a faculty member in the EECS department at the Univ. of California, Santa Barbara.

G.L. BLANKENSHIP, after receiving his Ph.D. from MIT, joined the faculty of Case Western Reserve University. He is now a faculty member in the EE Department at the Univ. of Maryland.

T.L. JOHNSON, after receiving his Ph.D. from MIT, joined the MIT EECS faculty. He is now with the General Electric Corporate Research and Development Center.

H.P. GEERING, after receiving his Ph.D. from MIT, joined Oerlikon Inc. He is now a faculty member in the ME Department at ETH, Zurich, Switzerland.

L.W. PORTER, after receiving his S.M. from MIT, joined the U.S. Air Force.

K.M. JOSEPH, after receiving his Ph.D. from MIT, joined TRW Inc.

R. CANALES, after receiving his Ph.D. from MIT, joined the EE Faculty at the Univ. of Mexico.

M.C. DELFOUR, after receiving his Ph.D. from MIT, joined the EE faculty at McGill University.

D.P. BERTSEKAS, after receiving his Ph.D. from MIT, joined the EE faculty at Stanford University, and then the Univ. of Illinois. He is now a faculty member in the EECS department at MIT.

N.R. SANDELL, JR., after receiving his Ph.D. from MIT, joined the EECS faculty at MIT. He is now President of ALPHATECH Inc.

R. KWONG, after receiving his Ph.D. from MIT, joined the EE faculty at the Univ. of Toronto.

C.Y. CHONG, after receiving his Ph.D. from MIT, joined the EE faculty at the Georgia Institute of Technology. He is now with Advanced Information and Decision Systems Inc.

A.H. SARRIS, after receiving his Ph.D. at MIT, joined the faculty of the Univ. of California at Berkeley. He is now a faculty member in the Economics Department at the Univ. of Athens, Greece.

J. DAVIS, after receiving his Ph.D. from MIT, joined the EE faculty at Queens College, Canada.

L.K. PLATZMAN, after receiving his Ph.D. from MIT, joined the Systems Engineering faculty at the Univ. of Michigan. He is now a faculty member in the OR department at the Georgia Institute of Technology.

D. WILLNER, after receiving his Ph.D. from MIT, joined the MIT Lincoln Laboratory.

R. KU, after receiving his Ph.D. from MIT, joined the General Electric Company.

A.S. WILLSKY, after receiving his Ph.D. from MIT, joined the EECS faculty at MIT.

S.I. MARCUS, after receiving his Ph.D. from MIT, joined the EE faculty at the Univ. of Texas, Austin.

P.K. WONG, after receiving his Ph.D. from MIT, joined the faculty at the Univ. of Malasia.

A.A. LOPEZ-TOLEDO, after receiving his Ph.D. from MIT, joined the faculty at the Univ. of Mexico.

D.N. MARTIN, after receiving his Ph.D. from MIT, joined Raytheon, Inc.

C.S. GREENE, after receiving his Ph.D. from MIT, joined Honeywell, Inc.

K.P. DUNN, was a post-doctoral fellow at MIT. He is now with the MIT Lincoln Laboratory.

M.G. SAFONOV, after receiving his Ph.D. from MIT, joined the EE faculty at the Univ. of Southern California.

D. TENEKETZIS, after receiving his Ph.D. from MIT, joined Systems Control Inc., and then ALPHATECH Inc. He is now a faculty member in the EE department at the Univ. of Michigan.

P.P. VARAIYA, was a visiting faculty member at MIT. He is with the EECS department at the Univ. of California at Berkeley.

T. ATHAY, after receiving his SM from MIT joined Systems Control Inc.

W.W. HAGER, after receiving his Ph.D. from MIT joined the EE faculty at the Univ. of Florida.

L.F. PAU, was a visiting post-doctoral fellow at MIT. He is with CNRS, Paris, France.

T.E. DJAFERIS, after receiving his Ph.D. from MIT, joined the EE faculty at the Univ. of Massachusetts.

S.B. GERSHWIN, is a Principal Research Scientist in LIDS at MIT.

D. FLAMM, after receiving his SM from MIT, joined the Aerospace Corp. Now he is back at MIT working on his Ph.D. thesis.

J.S.H. LIU, after receiving his Ph.D. from MIT, joined the Analytical Sciences Corp.

J.D. BIRDWELL, after receiving his Ph.D. from MIT, joined the EE faculty at the Univ. of Tennessee.

G. STEIN, is an Adjunct Professor at MIT, and also with Honeywell, Inc.

P.K. HOUPT, after receiving his Ph.D. from MIT, joined the ME faculty at MIT.

A.J. LAUB was a Research Scientist in LIDS at MIT. He is now a faculty member in the EE department at the Univ. of California at Santa Barbara.

D.A. CASTANON, after receiving his Ph.D. from MIT, was appointed Research Scientist in LIDS at MIT. He is now with ALPHATECH, Inc.

H. CHIZECK, after receiving his Ph.D. from MIT, joined the EE faculty at the Case Western Reserve Universtiy.

C.G. MCMULDROCH, after receiving his SM from MIT, joined the Boeing Aircraft Co.

P. MORONEY, after receiving his Ph.D. from MIT, joined Linkabit Inc.

E.Y. CHOW, after receiving his Ph.D. from MIT, joined Schlumberger Inc.

P.M. THOMPSON, after receiving his Ph.D. from MIT, joined the EE faculty at the California Institute of Technology.

N.A. LEHTOMAKI, after receiving his Ph.D. from MIT, joined Honeywell Inc.

A.E. YAGLE, is currently working on his Ph.D. thesis at MIT.

P. NG, is currently working on his Ph.D. thesis at MIT.

M. TRIANTAFYLLOU, is a faculty member in the Ocean Engineering department at MIT.

B.C. LEVY, is a faculty member in the EECS department at MIT.

L. VALAVANI, was a Research Scientist in LIDS at MIT and a staff member at the C.S. Draper Laboratory Inc. She is joining the Aero and Astro Faculty at MIT.

C.E. ROHRS, after receiving his Ph.D. at MIT, joined the EE faculty at the Univ. of Notre Dame.

M. BODSON, after receiving his S.M. thesis at MIT, went to the Univ. of California at Berkeley for his doctoral studies.

X.C. LOU, is currently working on his Ph.D. thesis at MIT.

G.C. VERGHESE, is faculty member in the EECS department at MIT.

J. KRAUSE, after receiving his SM from MIT, joined Honeywell Inc.

S.S. SASTRY, was a faculty member in the EECS department at MIT. He is now a faculty member at the Univ. of California at Berkeley.

K. HAIGES, after receiving his SM from MIT, joined the Northrop Corp.

D. ORLICKI, is completing his Ph.D. thesis at MIT and will join the Kodak Corp.

E. KAPPOS, after receiving his SM at MIT, went to the Univ. of California at Berkeley for his doctoral studies.

J.N. TSITSIKLIS, after receiving his Ph.D. from MIT, joined the EE faculty at Stanford University. He is now a faculty member with the EECS department at MIT.

G. GOODMAN, after receiving his SM from MIT, joined ALPHATECH Inc.

H.A. SPANG III, is an Adjunct Professor at MIT; he is also with the General Electric Co.

P. KAPASOURIS, is at present a doctoral student at MIT.

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ARC Technical Monitor: George Meyer
Final Report

16. Abstract

In this final report, we overview the research carried out over 18 years in the areas of optimal control and estimation theory and its applications under this grant. We also provide a listing of the 257 publications that document the research results. Finally, we present the list of the 80 MIT faculty, post-doctoral staff, and graduate students that participated in this research.

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